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An overview of thixoforming process

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Abstract. Thixoforming is a forming process which exploits metal rheological behaviour during solidus and liquidus range temperature. Many research works in thixoforming are currently focusing on the raw material used to produce superior mechanical properties and excellent formability components, especially in automotive industries. Furthermore, the thixoforming process also produced less casting defect component such as macrosegregation, shrinkage and porosity. These advantages are sufficient to attract more exploration works of thixoforming operation. However, the weakness of this process such as high production cost due to leftover billet which cannot be recycled, encourage researcher works to overcome thixoforming limitations by using various methods. The thixoforming methods that widely used are thixocasting, thixoforging, thixorolling, thixoextrusion and thixomoulding. Each method provides varieties of final product characteristics; hence offer the extensive possibility of component invention. On the other hand, new thixoforming method leads to exploration research such as microstructure evolution, heating and pouring temperature, die temperature, mechanical properties, viscosity and final product quality. This review paper presents findings in the rheological material behaviour of thixoforming, advantages and disadvantages of thixoforming, parameters affecting the thixoforming operation, morphology of thixoforming and various methods which have been used in this research area.

1. Introduction

Semisolid metallic alloys were discovered by Spencer in 1972 at MIT while investigated viscosity of Sn-15%Pb and found out during the experiment, semisolid state without stirring produce dendritic while the continuously stirred material was spheroidal [1]. Since then, extensive research regarding semisolid metal processing (SSMP) leads to various processes development. SSMP were applied in the industry due to the final product has less defect such as porosity, shrinkage, gas entrapment and macrosegregation [2]. SSMP can be categorized into two routes, namely rheocasting and thixoforming [3]. Rheocasting is a forming process start from liquid alloy, directly introduced into a die without any intermediate solidification step. The semisolid slurry in this route produced from an entirely liquid regular alloy. While thixoforming is a route consists of reheating and forming process. Thixoforming steps are feedstock billet with globular microstructure specially prepared, cut to length, reheated into solid-liquid temperature to achieve suitable solid fraction, then final product formed by various methods [4].

In the early years of SSMP research, scientists mainly focus on thixotropic material development because it was essential in both routes. The material in thixotropic condition was described as the ability of material to flow when shear force was given and it will thicken again when shear force was released [5]. Thixotropic condition happened due to globular microstructure in the material. Methods to gain fine globular microstructure such as Magnetohydrodynamic stirring, Strain Induced Melt



Activated (SIMA), Mechanical stirring, Cooling slope and Direct Thermal Method are widely used either for scientific research or industry application [6].

Thixoforming particularly needs feedstock billet which prepared by special method because solidification step is essential compared to rheocasting. Thixoforming also described as near net shape forming due to billet reheated into solid-liquid temperature and partially melted non-dendritic slug into a metal die [7].

In industry application, thixoforming was considered high-cost manufacturing because of raw material was not supplied widely [4]. However, this method offers broader ranges of design option which attract people in this area improves it continuously [8].

This paper focused on thixoforming and divided into four sections. The first section highlights the rheological material behaviour, the second part emphasises on advantages and disadvantages of thixoforming, the third section focuses on parameters affecting the thixoforming operation, the fourth division explained morphology of thixoforming and final section presents various methods have been used in this process.

2. Rheological material behaviour

Rheology is a term to describe deformation and flow behaviour of material. In SSMP, non-dendritic microstructures play the main role of semisolid state behaviour. Globular microstructure which gains from continuous stirring during cooling exhibits lower viscosity compared to a material with dendritic microstructures. Spheroid solid surround by the liquid matrix, is a requirement for semisolid processing and thixotropic condition. The thixotropic condition is explained as material decreases in viscosity if shear but stand still again if allowed [9].

Material or alloy in the semisolid state also referred as slurry, which can be divided into two categories: a liquid-like and a solid-like. Liquid-like named for slurry behaves like liquid under external shear due to dispersed solid particles. Meanwhile, solid-like slurry exhibits solid behaviour because of containing interconnected solid phase [6]. In thixoforming process, solid-like slurry is involved. Solid-like slurry with thixotropic condition has the ability to flow in laminar, which uniform flow during forming is possible.

Viscosity is the main parameter for rheology in semisolid processing. Viscosity indicates capabilities of semisolid material in filling mould, flow behaviour and required force for deformation [10]. The viscosity in semisolid metal was influenced by solid fraction, particle size, and particle distribution. Solid fraction was defined as the density of solid in the semisolid slurry. Solid component was generated by partial solidification of slurry [11]. For thixoforming processing, effective solid fraction is between 0.5 and 0.6. If the solid fraction is below 0.5, the slug cannot support its weight and consider as too soft. Whereas, if solid fraction is over 0.6, the slug will not be able to fill the die because too stiff to flow [12].

3. Advantages and disadvantages

Thixoforming process like any other operation, hold its own benefits and limitation. As for advantages, thixoformed parts reported have higher quality compared to conventional produce. Better quality products of thixoforming were gain due to globular microstructure. Spheroidal microstructure provides flow ability in billet during forming. Less shrinkage, gas entrapment and porosity parts were created from slug flow in laminar. Other than that, mechanical properties of final product were enhanced by fine and uniform microstructure. Due to fine and uniform structure, thixoforming operation able to create wide range of component shape with different wall thickness, sharp edged and radii edge [4-6, 8, 9, 11-15].

However, limitations of thixoforming process may cause less response in industry. The most well-known shortcoming of thixoforming was special requirement for feedstock billet may increase production cost. Besides, scrap from forming process cannot be recycled. Furthermore, to ensure final product quality, knowledgeable supervise were needed for each step. Moreover, crucial points in thixoforming operation were viscosity and solid fraction. Both were dependent on temperature control, therefore, high technical personnel were needed for accurate temperature control. Even though SSMP

has taken places in research light for 40 years, continuous research in thixoforming is necessary to support development of new components [4-6, 11, 16].

Identifying leads and shortcomings of thixoforming will lead to deeper investigation, thus improve thixoforming in many aspect. Recently, researchers focus on thixoforming as changed from development of technique produce feedstock billet into improvement of cost saving thixoforming operation.

4. Parameters affecting thixoforming process

Since the expansion of thixoforming research takes place, many research appoint parameter affecting thixoforming based on critical criteria for thixoforming to be successful.

4.1. Solid fraction

Viscosity of material during thixoforming highly influence by solid fraction. In SSMP, suitable solid fraction usually in range of 30% - 70% [17, 18]. Low solid fraction indicates high viscosity, thus slurry flowing ability during forming will be lower.

Ahmad et al. conduct an experiment to find effect of cooling rates on thermal profiles aluminium alloy 7075. They pour molten metal into chamber with Kaowool blanket then, thermocouples were inserted at the centre and near cubicle wall. Temperature differences were plotted against time to determine dendritic coherency point. Through the experiment, they found that fraction solid were affected by cooling rates. From graph plotted, the different value of fraction solid for slow cooling rates and high cooling rates were at 0.7 fractions solid. This investigation exhibits the effect of cooling rate on solid temperature and liquid temperature which is crucial during reheat in thixoforming process [17].

Earlier than Ahmad et al., Nafisi et al. investigate fraction solid during processing temperature with the same set up. Melts were prepared in silicon carbide crucible which later transferred into cooling stand and K-type thermocouple inserted at two locations. In this experiment, they processed data using computer aided cooling curve analysis (CA-CCA), computational thermodynamic and quantitative metallography. They concluded inefficient during quenching methods lead to more primary α -Al formation as the main reason for fraction solid differences in the experiment [19].

4.2. Particle size

Thru understanding of SSMP, smaller or finer particle size of material is expected to provide smooth filling movement and less viscose. However, through various experimental, particle sizes are much affected by temperature such as pouring temperature, tool temperature and cooling rate.

El-Mahallawi et al. investigated effects of pouring temperature and water cooling on semisolid microstructure of A319 aluminium cast alloy. This experiment started with A319 melted in electric furnace and allowed to cool down to specified pouring temperature before continuously poured on cooling slope. For each temperature, pouring was carried out with and without water cooling. They found that ingots with water cooling show lower bulk porosity and increasing pouring temperature slightly reducing bulk porosity. Other than that, they discovered ingot with water cooling exhibits lower shape factor and with increasing pouring temperature accumulate shape factor of α -Al grains. Furthermore, they also found that water cooled ingot shown lower average grain size and with increasing pouring temperature accumulate average size of primary grains [20].

5. Morphology of thixoforming

In investigation of thixoforming, microstructures were frequently used to analyse relationship between process and mechanical properties. Based on experiment by Tavakoli et al., cooling slope method and thixoforming were proven improved mechanical properties of A380 alloy, such as tensile strength, elongation and hardness [21].

Lee et al. has produced 6061 wrought aluminium alloy feedstock billet from thermo-mechanical method and thixoextruded it into automotive component. The research was concentrated on the possibility of thixoformed 6061 into steering knuckles. The grain size distribution of the steering knuckles from this research is presented in figure 1. This research finding showed that 6061 was able

to be produced by thixoforging operation which ductility and strength were significantly increased after T6 heat treatment [22].

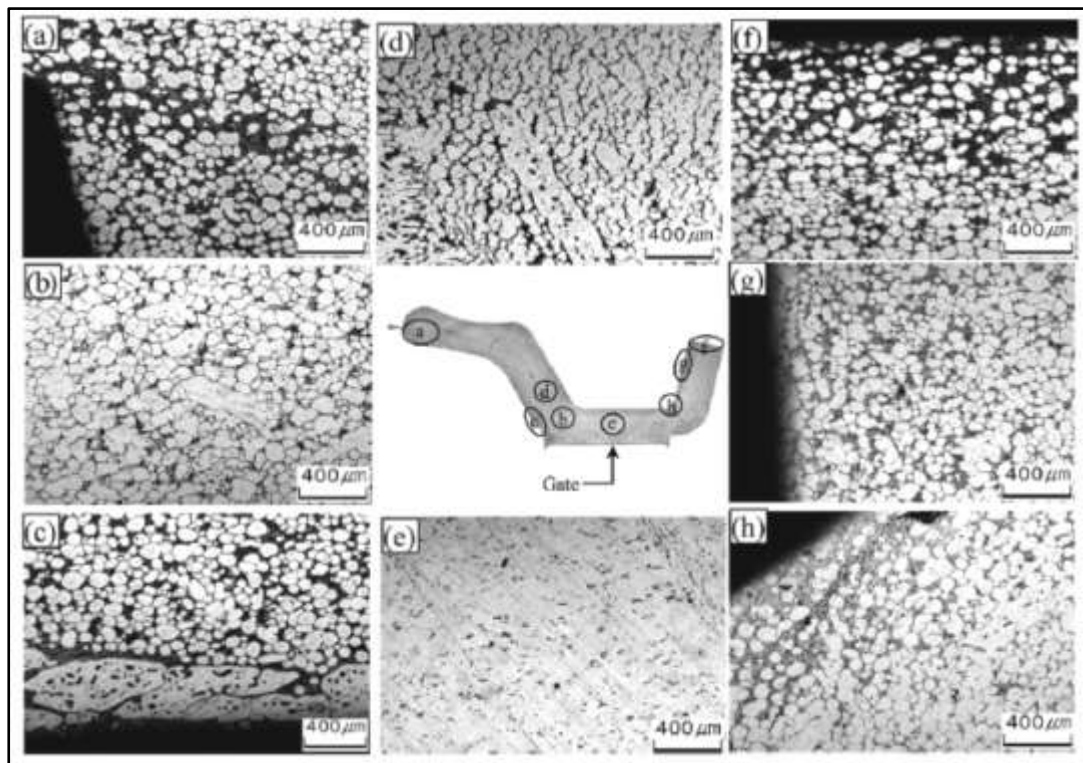


Figure 1. Microstructures of steering knuckles which shown fraction solid distribution at different area [22].

6. Various forming method

In the early years of SSMP, forming method mainly same as conventional, the difference is SSMP using globular microstructure feedstock billet. For thixoforging, after billet is reheated into semisolid temperature range, forming shortly takes place. Following are few of thixoforging methods.

6.1. Thixoforging

Thixoforging is a process similar to closed-die forging. Billet is placed between open die halves and pressed to form final product. In this process, billet with lower liquid fraction is significantly used. This method able to produce product with variable wall thickness, sharp radii and sharp edge thickness changed [16].

Jung et al. conducted an experiment to determine reheating process for cast and wrought aluminium alloy for thixoforging. They achieve optimal reheating by controlling holding time and relevant temperature for each step using induction heating. From this experiment, they find that suitable temperature for each step in thixoforging will lead to high quality product. Since fluidity of billet during forming have high influenced on final product, reheating holding time were take account. If the reheating holding time were too long, risk for grain coarsening will increase too [23].

Meanwhile, Cho et al. has done experiment on mechanical properties of thixoforging product. This experiment, researcher observing filling behaviour during forming, investigates defects on product and final product mechanical properties. They used A356 and Al2024 (wrought) with different die temperature to find die temperature filling limitation. From the research, results shown that ultimate tensile strength and yield strength were increase at higher applied pressure. Other than that, highest hardness degree was shown at the center of area. This happened due to edge of the area have higher liquid distribution during forming [24].

As research of thixoforging using aluminium alloy expanding tremendously, Wang et al. investigated microstructural evolution and mechanical properties of 9Cr18 steel after thixoforging. Through this research, they found out optimal heat treatment for 9Cr18 steel thixoforging is at 550° C for 2 hour. Strong hardening at the inner area was observed and compressive strength of 4680 MPa were achieve with compressive strain of 53.3% [25].

6.2. Thixocasting

In thixocasting, billet is shot into a closed-die by piston to form and usually used billet with liquid fraction in range of 40% - 60%. During forming in thixocasting, laminar flow of slug is critical aspect in ensure high quality product [6]. Shown in figure 2 is difference process for thixoforging and thixocasting method.

In order to understand filling or flow in thixocasting, scientists develop software to calculate and have better picture of product forming using thixocasting method. Modigell et al. investigate tin lead alloy (Sn-15%Pb) rheology by changing shear rate under isothermal conditions. Data from experimentation later compared to model develop by using commercial CFD software. Results from this experiment exhibit filling velocity give high impact on product quality [26].

Another experiment on rheology behaviour for thixocasting is conducted by Yang et al.. Aluminium alloys (A356) were thixocasted and compared to model. From their calculation, it is proven rheological behaviour of semisolid metal during thixocasting is pseudoplasticity of non-Newtonian. Their calculation has open to better understanding of filling flow during thixocasting and provide improvement in producing higher quality product using thixocasting method [27].

While, Kim et al. used thixocasting method to produce possible high strength Mg-Cu-Y alloy. Magnesium alloy is an attractive material for aeronautic transportation application industry because of its light weight properties and excellent damping capacity [28, 29]. However, magnesium alloy were limitedly found in industry is cause by its poor corrosion resistance. Thru thixocasting, Mg₉₀ Cu₅ Y₅ alloy exhibits high tensile strength compared to conventional magnesium. Researchers explained that globular magnesium as primary particles were surrounded by liquid quenched (partly amorphized) with later transform into hard amorphous. This microstructure has improved Mg-Cu-Y alloy strength[29].

Other than using slug, researchers also extend their interest towards powder thixocasting. Chen et al. investigation shown powder thixocasted Al-Si powder provide good formability with satisfied strength and uniform distribution of Si particles [30].

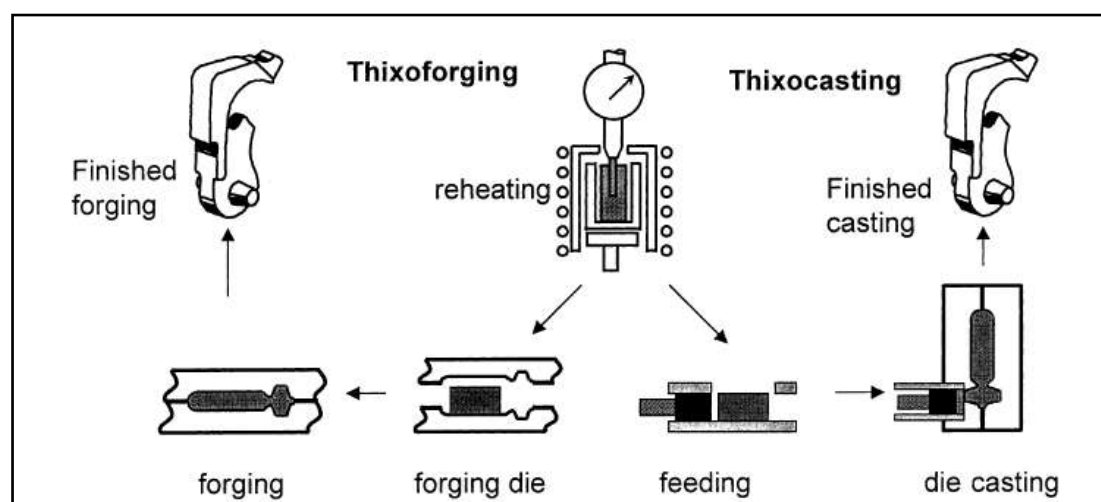


Figure 2. Illustration of thixoforging and thixocasting process[6].

6.3. Thixomoulding

Thixomoulding is a process to produce near net shaped component from magnesium alloy. This process took place in a single integrated machine as shown in figure 3. Magnesium alloy chips in

range size of 2-5 mm feed into machine and heated until partial melted. Partial melted alloys transform into semisolid slurry. Huge and high speed screw later injects slurry into mould for final product forming. As magnesium alloy would oxidize when heated, an argon atmosphere was maintained at in-feed. Thixomoulding is an effective process of thixoforming because involved only one step process[6, 31, 32]. However, thixomoulding only available for magnesium alloy production because other alloy such as aluminium alloy would likely attack the barrel and screw while in semisolid state[5].

To evaluate capabilities of thixomoulding system in processing magnesium alloy, Czerwinski operate an experiment using a Husky's prototype system named TXM500-M70. The researcher used mechanically chipped magnesium alloy as material. In this experiment, major operating parameters are cylinder barrel temperature, screw rotation speed, injection velocity, injection pressure and mould temperature. Thru this experiment, Czerwinski conclude that temperature along injection mould is the key factor in controlling process. While, solid fraction and injection velocity were influenced flow behaviour of magnesium alloy slurry during mould filling [33].

Furthermore, thixomoulding is seen as potential near-net shape method which could provide effective energy usage and less pollution. Thus, Patel et al. conduct an experiment focusing on evaluating thixomoulded AZ91D and AM60B due to its flexibility in fabrication, high strength-to-weight ratio besides increasing usage in automotive industry. from this experiment, for fracture characteristic, AZ91D exhibited cleavage like fracture with secondary crack while AM60B shown dimple like features due to formation and coalescence microvoids. Ultimate tensile strength for both were shown equivalent within experimental scatter. AZ91D alloys displayed higher yield strength and lower ductility compared to AM60B. Characteristics of both alloys revealed in this experiment were lead to deeper understanding of their production through thixomoulding method [34].

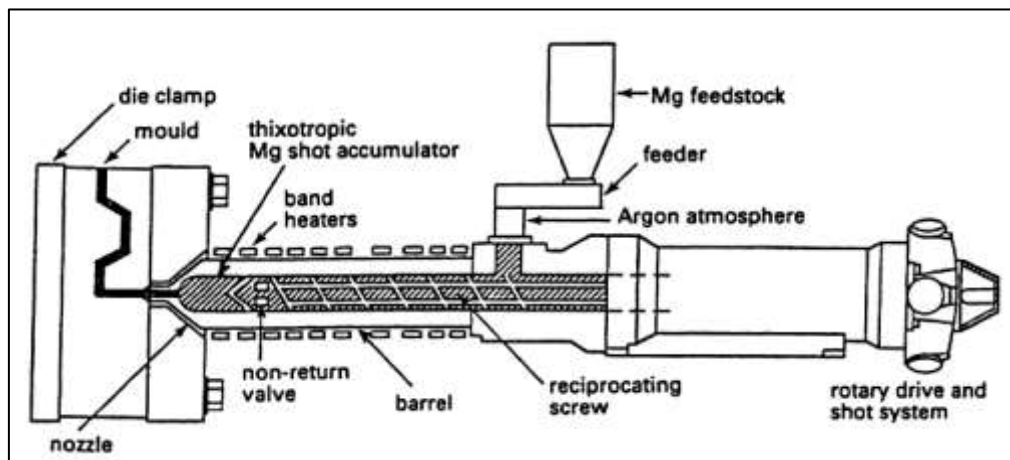


Figure 3. Diagram of a thixomoulding machine [6].

6.4. Thixorolling

Rolling is a process where materials were undergoes two rollers which produce flat like metal [35]. In thixorolling, slug or reheated billet with globular microstructure were flowed through two roller and produce alloy strip. Semisolid Powder Rolling (SSPR) is said possible for industrial application and its product possible to be used in aerospace application [36].

Liu et al. investigated microstructural evolution of 7050 aluminium alloy during SSPR. Researchers used gas atomized 7050 aluminium alloy powder which, reheated to semisolid temperature and inserted into inert atmosphere with different period. They observe that the most suitable liquid fraction for SSPR is 45 – 65 %. Alloy strips can be produce with nearly full density and high micro-hardness. They highlight three important mechanisms in this technique which are filling and flowing of liquid, solidification by rolling and recrystallization [37].

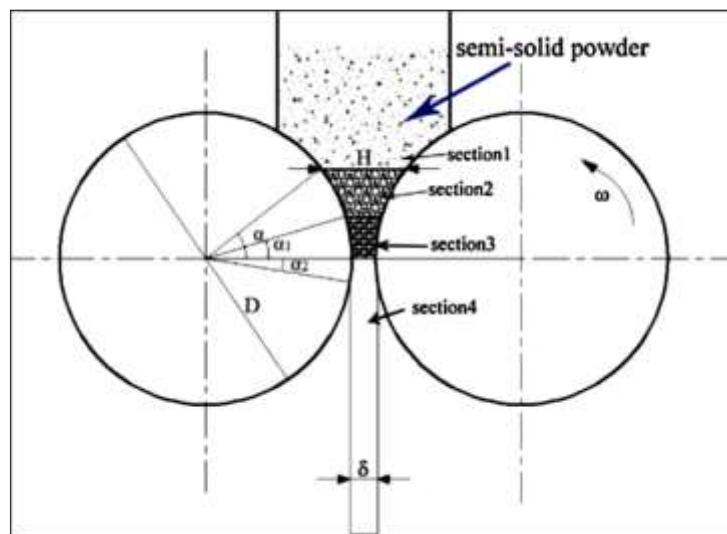


Figure 4. Schematic picture of semisolid powder rolling [37].

6.5. Thixoextrusion

In thixoextrusion, reheated billet with globular microstructure were squeezed into an already closed die [38-40]. Like any other thixoforming method, thixoextrusion offer several advantages compared to conventional extrusion such as higher material fluidity, lower pressure and longer tools life. Thixoextrusion also offer production of hard-to-form aluminium alloys for automotive industry [38].

Rovira et al. has done experiment thixoforming of Al-Cu alloys by using thixoforging and thixoextrusion. They compared thixoforming method with conventional processing, proved thixoextrusion produce final product with fine and equi-axial structure besides lower energy use [41].

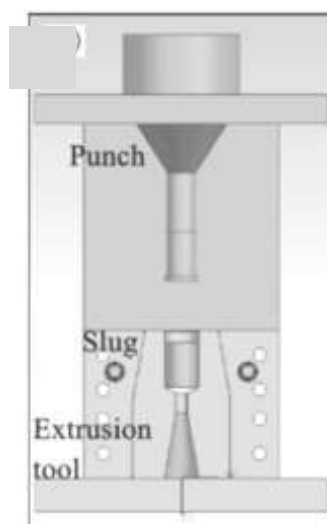


Figure 5. Example outline of extrusion tool by Forn et al. [38].

7. Conclusions

This overview shows thixoforming process for component forming by using semisolid principle. These methods were applied in several industries worldwide such as automotive and aerospace. This review appoints that effective route for thixoforming development is understanding rheology behaviour of material during process. Likewise, highlighted identified benefit and limitation of thixoforming gives deeper comprehension of this operation. Although thixoforming operation was applied in industry, continuous study on material aspect for this process still needed as an effort to

accommodate future industry requirement. Nevertheless, thixoforming is still providing wider possibility production of high quality components compared to conventional.

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